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Research on plasma interaction with materials for thermonuclear reactors in the Russian Federation

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Abstract

The short review of art of state of research in Russian Federation in the field of plasma surface interactions (PSI) related to the problems of plasma-faced materials in controlled fusion devices is presented. The most activity in this field in RF is concentrated on the theoretical, computer and experimental simulations of processes taking place at plasma and its components interactions with condensed matter. The main recent results in PSI obtained in RF are shortly listed including studies of elementary processes accompanied steady state plasma interactions with materials and components as well as results obtained during high power pulsed plasma simulations of transients and disruptions in tokamaks. Detailed list of recent publications is also presented.

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Keywords: plasma-surface interaction; fusion; Russian Federation

1. Introduction

In Russia, the field of research activity on the plasma surface interactions (PSI) related to the problems of controlled thermonuclear fusion is wide. In this review, the main Russian scientific groups as well as their topics and

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a brief summary of the results obtained during the last two - three years are listed. The last results presented during the conference on PSI held at MEPhI in February 2015 one can find in this issue of the conference Proceedings.

If we divide the PSI studies in Russia into those that are conducted in fusion devices and those that can be considered as experimental, theoretical or computer simulations, the latter predominate. This is attributed to the limited experimental base.

2. Experimental base for PSI studies

The largest Russian tokamak, T-10, with a circular plasma cross section and without a divertor, underperforms compared to the larger foreign tokamaks. The only divertor tokamak in RF is the small spherical tokamak Globus-M. PSI-targeted investigations in this tokamak have started quite recently. In addition, intensive and promising researches with Li as a plasma facing material (PFM) have been successfully performed in the T-11 tokamak at TRINITI. Unfortunately, a limited number of our scientific groups collaborate fruitfully with foreign teams conducting experiments in large tokamaks. For example, it is worth mentioning the IPP (Germany) - MEPhI collaboration in the post-mortem analysis of tiles from JET [S. Krat et al. (2013, 2015)] and the Tore Supra team – MEPhI collaboration during the last decades [Airapetov et al. (2011), Hodille et al. (2014)].

In the field of experimental studies of pulsed high-power PSI modeling of transients, edge localized modes (ELM) and disruptions in tokamaks, we still hold the leading positions due to active experiments at accelerators QSPA [Klimov et al. (2014)] and MK-200 (TRINITI) that for a long time did not have analogues abroad. Moreover, the base of research in recent years has expanded with the launch of QSPA-Be in Bochvar [Kupriyanov et al. (2014)] institute for operation with beryllium and application of high power pulsed electron beam (of 10 μs duration) to PSI studies at the GOL-3 facility in Novosibirsk [Arzhannikov et al. (2013)].

The number of linear stationary simulators with a longitudinal magnetic field, is constantly growing in the world, while plasma parameters have become closer (plasma concentrations up to 10^{15} cm^{-3}) to those in the ITER divertor (PILOT-PSI, MAGNUM-PSI) due to the usage of arc plasma sources and a strong magnetic field. In our country, linear simulators with plasma initiated by an electron beam (plasma-beam discharge) are in operation. These are LENTA at Kurchatov Institute (NRC KI) and PR-2 at MEPhI with the maximal plasma density of approximately two orders of magnitude lower as compared to MAGNUM-PSI.

The lack of modern large linear simulators is compensated by paying more attention to the physics of the PSI interactions studied in the specialized laboratory setups. The number of such laboratory facilities and topics of investigations are continuously increasing in RF. It is worth mentioning MEPhI, where over the past few years a number of new units and stands have been put into operation including the UHV thermal desorption (TDS) stand, the MD-2 magnetron-based TDS facility [Krat S. et al. (2014)], the MIKMA multifunction installation allowing irradiation of samples with both plasma and neutrals and simultaneous or consequent TDS analysis [Airapetov et al. (2011)]. The CODMATT facility put into operation last year is of particular interest [Azizov et al. (2015)], as it allows deposition of coatings and high heat testing of materials under conditions close to those in ITER. Samples in CODMATT can be irradiated with pulsed ion fluxes with the power density up to 20 MW m^{-2} of 1-5 ms duration and the repetition rate up to 1 kHz.

The first results from the ion beam facility (ILU) in RNC KI allowing simultaneous irradiation of samples with both a keV ion beam and an intensive electron beam (2.5 keV, 0.15-1.5 A/cm^2) have recently been reported [Martynenko et al. (2013)].

Furthermore, there is a broadening list of techniques used for PSI analysis, including novel analytical devices such as FIB, SEM, electron microscopes with elemental analysis, different diffractometers and synchrotrons. Principally new methods, like, for example, in situ (during exposure to plasma) ion scattering spectroscopy analysis of composition and thickness of the films on the surface [MEPhI, Mamedov (2012)], have been recently developed as well.

3. The new experimental effects

Among the new experimental results replenishing the database on PMI and enhancing the understanding of the physics of PSI, we should mention the results obtained at NRC KI on the dramatic increase of the sputtering yield of metal targets under simultaneous ion and electron bombardment [Martynenko et al. (2013)]. This situation is relevant in principle to fusion reactors, where the PFCs are irradiated with ions accelerated by sheath potential and electrons from the Maxwell tail. This phenomenon of enhanced sputtering have been explained to be due to the generation of adatoms on the surface under ion sputtering with consequent association of adatoms into clusters that, in turn, facilitate binding with the surface and evaporate more easily under electron irradiation [Martynenko et al. (2013)].

It has been shown for the first time (MEPhI) that in the presence of thin oxide layers (which can exist on Be and W) on the surface, oscillations can occur in the tube of plasma connected to such a surface. These oscillations are accompanied by the growth of the plasma wall potential difference (and, as a consequence, by the irradiation of the surfaces by ions of high energy) [Gutorov et al. (2012)]. The model proposed by proposed Gutorov et al. (2014) has provided an explanation for the observed current-voltage characteristics (CVC) of the plasma-surface transition, including the presence of a CVC step change and a negative resistance region.

4. PFC behavior under high heat loads

The study of the PFC behavior under high heat loads corresponding to plasma disruptions in tokamaks, powerfull ELMs and transients at plasma accelerators QSPA-T (TRINITI) and QSPA-Be (Bochvar) has demonstated that Be erosion increases significantly with the temperature increasing from 250 to 500 °C [Putrik et al. (2014)], which may necessitate more effective ITER first wall cooling than provided now. An unexpected difference has been found in the evolution of different grades of stainless steels (ITER grade 316L(n)-IG and Rusfer steel manufactured in Russia) for ITER pipes under photonic radiation from the zone of the plasma interaction with the divertor target in a simulation of mitigated ITER disruptions [Klimov et al. (2015)]. Repeated exposure of the steel leads to a regular, “corrugated” surface with hills and valleys, which were clearly observed already after 5 pulses for all investigated steel grades. Repeated 0.5ms 2MJ/m2 pulses at QSPA-T lead to melting and resolidification of the Russian BM-P tungsten grade, resulting in the generation of a resolidified layer of 50µm thickness. The cracks both normal and parallel to the surface have been observed that could result in the brittle destruction, which is a hazard for the full-tungsten divertor of ITER [Budaev et al. (2015)].

5. Hydrogen isotopes retention, permeation and desorption

A large amount of work (MEPhI, TRINITI) has been performed on hydrogen isotopes accumulation in PFC**.** It has turned out that the capture of deuterium at high rates (three orders of magnitude higher as compared to stationary deposition) of W deposition in QSPA-T is two times higher and scales with the deposition rate R_D with the same power $\sim R_D^{-0.4}$ [Klimov et al. (2014)]. This is similar to that at much lower deposition rates in the stationary regime ($0.01\text{-}2.0\times10^{15}$ $\text{at}\cdot\text{cm}^{-2}\text{s}^{-1}$), and correlates to previously proposed De Temmerman and Doerner (2009) scaling. Due to the very high deposition rate during transients, such short time events will cause main hydrogen isotopes retention in PFC.

Deuterium retention studies with different grades of beryllium after irradiation with 0.5 ms 0.4 – 0.5 MJ/m^2 pulse at QSPA-Be [Kupriyanov et al. (2014)] has shown that the main part of deuterium desorbs at high temperatures in the range 900–1350 K, but the total content of D (after 10 shots) is small (3×10^{-6} to 6.3×10^{-5}).

The phenomenon of rapid removal of hydrogen isotopes from PFC with thin oxide layers under irradiation with hydrogen atoms in a hydrogen atmosphere with oxygen admixture or with ions from hydrogen plasma with an oxygen admixture has been experimentally found and explained. It has been suggested that the phenomenon can be used for low-temperature degassing (400 °C, 200 °C) of plasma chamber [Begrambekov et al. (2015)].

Active research of hydrogen retention as well as hydrogen permeation through structural fusion materials has been carried out at NRC KI. The recent activity related to the He influence on hydrogen isotope exchange, and it was shown that exposure of D-saturated W samples to He/H plasma reduces the amount of released D as compared to pure protium plasma [Bobyr et al. (2015)]. It was also found that gas-driven permeation of deuterium for V-4Cr-4Ti alloy is 4 orders of magnitude higher as compared with Rusfer steel and austenitic steel ChS-68 [Spytsin et al. (2014)].

The effect of radiation-induced defects influence on the accumulation of deuterium in W has been intensively studied. At the NRC KI, cyclotron light ions H, He, Li, C with the energy of 1-60 MeV were used to create defects up to 600 dpa in tungsten with subsequent irradiation with 250 eV deuterium ions at LENTA facility. Deuterium retention in W damaged by He irradiation demonstrates both decrease and increase depending on the quantity of implanted He and structure of the surface layer [Khripunov et al. (2013)].

The joint research IPP (Garching) - MEPhI team used W ions with the energy of 20 MeV for damage production. Nuclear reaction analysis (NRA) with 4 MeV 3He at IPP was made to measure the D depth profile. In particular, it was shown that significant deuterium amount can be accumulated in W at high wall temperature 800 K, [Ogorodnikova et al. (2014)], and defects with the detrapping energy of 1.7-2.0 eV play a major role at these temperatures [Gasparyan et al. (2015)]. D retention in W with admixture of 1.1% TiC and 3.3%TaC at room temperature is comparable to that for pure unrecrystallized W (due to the small range of the implanted low energy ions in the damaged near-surface layer), but at a higher temperature (of 600 K), retention in doped W is much higher than in pure W [Zibrov et al. (2014)].

6. Hydrogen isotopes retention, permeation and desorption

Impurity deposition on the surfaces of diagnostic mirrors and methods of mirror cleaning are the subject of investigation in several groups. The main activity in this field is concentrated at the A.N. Frumkin Institute of Physical chemistry and Electrochemistry RAS (IPCE RAS). Deposition and destruction of films have been studied in a special installation with glow discharge at IPCE RAS with definition of different molecular species sticking coefficients, influence of oxygen on selective hydrocarbon films removal from W surface. It has been shown that oxidized layers of a few hundred nm thickness can appear on the some grains of W surface that can result in dust generation [Zalavutdinov et al. (2014)]. Experiments with W and Al sputtering in D_2/O_2 plasma have found linear dependence on the negative bias potential. It has been proposed that the maximum sputtering rate corresponds to the situation where all oxygen atoms in the plasma contained in molecular species (D2O, DO) [Bukhovets et al. (2015)]. Different methods of analysis (XPS, XAES, ellipsometry) of films were used in tokamak T-10 and pulsed machine QSPA-T. On the ternary phase diagram (H,Csp^2, Csp^3) films for both machines localized in the compact region between diamond-like and polymer like a-CH films [Arkhipov et al. (2013)].

Investigations of hydrocarbon film deposition in a discharge with HF oscillations (MEPhI) have shown that the presence of the HF component in the plasma promote film precipitation in the regions shadowed from the plasma. On the other hand, the purification of precipitations with oxygen in the presence of HF waves considerably speeds up the process [Gutorov et al., these proceedings].

It is worth mentioning the work on tungsten protection with renewable sacrifice coatings that can be deposited during a working discharge in ITER. Boron carbide has both low sputtering yield and hydrogen retention [Azizov et al. (2014)]. Demonstration of the possibility of such a solution would eliminate tungsten destruction during thermal cycling due to ELMs.

7. Hydrogen isotopes retention, permeation and desorption

Russian activity in the field of Li application in fusion devices started in 1996 with the proposal of capillary-porous system (CPS) as PFC. Now it is concentrated in the “Red Star” (I. Lyublinsky et al.) and TRINITI (S.Mirnov). New CPS-based elements with a hard matrix made from stainless steel mesh, Mo or W eliminate the Li flux into plasma, its pollution and Li accumulation [Lyublinski et al. (2015), Mirnov et al. (2014), Vertkov et al.

(2014)]. Some experiments on Li film interaction with hydrogen isotopes have been carried out at MEPhI [Krat et al. (2014)].

8. Theoretical and computer studies

Theoretical studies of the PSI processes are mainly concentrated in NRC KI and MEPhI. It is worth emphasizing the work carried out by Yu.V.Martynenko (2012) (NRC KI) with the model of fuzz formation on hot tungsten surfaces irradiated by helium ions. Budaev et al. (2015) proposed a model a model of the crack formation on tungsten under cyclic heat tests. An interesting prediction is that the most dangerous cracks parallel to the surface may occur only in thin layers and therefore may not be dangerous for ITER [Kukushkin et al. (2012)].

Krasheninnikov and Marenkov (2014) have proposed a model with a continuous energy spectrum of traps in the PFM exposed to plasma, which explains the experimentally observed thermal desorption spectra (TDS) and the time dependence of outgassing in the JET tokamak. They have also predicted instability in the surface-plasma exchange caused by the temperature dependence of gas release from PFM and enhanced radiation losses from the plasma with its concentration increase due to the growth of wall outgassing [Marenkov et al. (2013)].

Other MEPhI theoretical activity in PSI related to calculation of the sheath potential distribution in a magnetic field and its influence on the secondary electron emission from PFM and its sputtering in a fusion reactor [Borodkina and Tsvetkov, these proceedings]. Accurate consideration of the transport phenomena in low-temperature multicomponent edge plasma in a magnetic field has allowed the derivation of expressions for dust particle stopping and their rotation [Stepanenko and Krasheninnikov (2013)].

Along with the analytical study of the PSI, computer codes describing features of plasma particles interactions with PFC has been developed. Monte Carlo code SCATTER [Koborov et al. (1997)], algorithmically close to the well-known code TRIM, have been improved by D.Kogut to describe the evolution of the PFC surface with 3D objects, such as cracks, drops and holes under irradiation by ions and charge exchange neutrals [Kurnaev et al. (2011)]. The quantative parameters of redeposition, sputtering and change the composition of the diagnostic mirror surface in ITER have been simulated, taking into account the fuel and Be impurities bombarding the diagnostic ducts walls made of stainless steel [Kogut et al. (2013)]. The evolution of a rough Be first wall, with microrelief corresponding to the mechanical treatment of Be tiles and retention of tritium in it as function of Be content in plasma with parameters taken from B2-EIRENE code and position of the PFC in the chamber were investigated [Kogut D.K. et al. (2013)]. It is interesting to note that dose-dependent T content in some cases saturates and decreases with time of operation due to competition of Be deposition and relief smoothing.

A new model, which describes the plastic deformation in materials with brittle-ductile transition in the heated surface layer, the conditions of the formation and evolution of cracks during thermal pulse loads has been developed by Arakcheev et al. (2015) (BINP, Novosibirsk).

9. Conclusion

Thus, a comparison of presented RF activity in PSI research with the survey of PSI results, including those performed in RF, presented at the 19th PSI conference (San Diego 2010) [Kurnaev et al. (2014)] shows that the range of topics and the scale of activity in RF has increased noticeably. Hopefully, this positive trend will continue with putting the T-15 divertor tokamak into operation in 2016.

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